CROSSTEX – Wave Breaking, Boundary Layer Processes, the Resulting Sediment Transport and Beach Profile Evolution

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Award Number: N00014-07-1-0154, N00014-05-1-0082

LONG-TERM GOALS

To develop and test with laboratory and field data a robust modeling framework that predicts hydrodynamics and the fate of terrestrial and marine sediment in the heterogeneous environment.

OBJECTIVES

- Develop phase/depth-resolving numerical models for bottom sediment transport and surf zone hydrodynamics. Validate these models using data measured in CROSSTEX and other field experiments.

- Identify the role of undertow current, steep waves and breaking wave turbulence on sediment suspension events.

- Develop simplified phase-resolving formulations for concentrated sediment transport, suspended load transport and its near-bed boundary conditions under breaking waves.

APPROACH

A two-phase flow model (Hsu et al 2004; Amoudry et al. 2007) is extended to model sand transport driven by measured random wave-current forcing during CROSSTEX (Scott et al. 2007). Measured near-bed time series of flow velocities are analyzed to extract (approximately) the time series of averaged wave velocities and turbulence quantities (TKE and dissipation rate). These time series are then used to drive the two-phase flow model and to calculate and resulting sand transport from immobile sand bed to the dilute region of about 5 cm above the immobile bed. Physical experiments also provide measured suspended sand concentration in the intermediate to dilute region (volume concentration ~<15%), which can be used to identify the suspension event and to validate the numerical model. On the other hand, two-phase model results for concentrated sediment dynamics can bridge the missing information at the regime of concentration from about 15% to random-close packing (~63%), which is difficult to measure in the physical experiment.

Because it is non-trivial to separate turbulence from the wave motion in the measured velocity time series, also because it is perhaps unclear at this point what is the major cause (e.g., steep wave or

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **CROSSTEX - Wave Breaking, Boundary Layer Processes, the Resulting Sediment Transport and Beach Profile Evolution**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Woods Hole Oceaographic Institution,MS#12,360 Woods Hole Rd,Woods Hole,MA,02543**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

breaking wave turbulence) of the strong sediment suspension event, it is critical to utilize a more powerful data analysis tool than commonly used Fourier analysis. Wavelet analysis is able to identify not only the steep oscillation events but also their (temporal) scale. Hence, more information can be extracted from the measured time-series when using wavelet analysis in conjunction with Fourier analysis. Wavelet analysis on the CROSSTEX data is investigated in collaboration with Dr. Nicolas Scott of Naval Research Laboratory.

WORK COMPLETED

CROSSTEX is a collaborative research project aiming at quantifying various mechanisms of wave- and current-induced sediment transport in the surf zone. The physical experiment of CROSSTEX was completed in Sep 2005 at O. H. Hinsdale Wave Laboratory of Oregon State University (Scott 2006; Scott et al. 2007). The experimental design of CROSSTEX is to mimic the field condition of onshore/offshore sandbar migration events observed during Duck 94 (Gallagher et al. 1998) so that possible mechanisms controlling the onshore/offshore sediment flux can be carefully studied.

Even in a well-controlled laboratory facility, detailed sediment transport in the concentrated regime near the bed cannot be measured with high temporal and spatial resolution. In this study, we utilize a two-phase model, which resolves both the bedload and suspended load, to link the missing information in the concentrated regime of transport. The two-phase model for sand transport has been validated in the past two years with published laboratory U-tube results (Amoudry et al. 2007). This year, we also extend the model with nonlinear boundary layer terms (i.e., approximate $\partial/\partial x \approx c^{-1}\,\partial/\partial t$ in the 2D two-phase equations with c the wave celerity) to mimic sediment transport under progressive waves. The model is validated with SISTEX99 data (Dohmen-Janssen and Hanes 2004) in order to investigate the effect of nonlinear streaming on wave-induced transport (Trowbridge and Young 1989; Henderson et al. 2004) in comparison with wave skewness/asymmetry and undertow current (e.g., Gallagher et al. 1998, Hsu and Hanes 2004). In the meantime, the two-phase model is also modified to be driven by measured wave velocity and turbulence (both TKE and turbulent dissipation rate need to be used) and reproduce sediment concentration similar to observation (see Fig 1).

A collaborative effort between UF/WHOI and Dr. Nicolas Scott (Naval Research Laboratory) is initiated earlier this year to analyze CROSSTEX data using wavelet transform. Morlet wavelet transform has been previously shown to be effective in identifying steep wave in open ocean (Scott et al. 2005). Similar method is applied here to the measured velocity time-series (50 Hz sampling rate). According to analysis done in the prior years, the cross-shore velocity component has both wave and turbulence information in the frequency range 1-2 Hz, while the along-tank velocity component has clean turbulence information. This suggests that the wavelet analysis must be applied currently to cross-shore and along-tank components to obtain a better understanding of steep wave and breaking wave turbulence. When plotting the wavelet transform results for velocities along with measured sediment concentration time series at different level above the bed, we can identify suspension events driven by (1) steep wave only (2) steep wave and breaking wave turbulence and (3) breaking wave turbulence only (if occurred). It is our hope to come up with useful statistics relating sand suspension events with steep wave and breaking wave turbulence. This information will be used to drive the two-phase model in order to further relate the hydrodynamic forcing to net sand transport flux.

In the previous years, the 2D RANS wave model (COBRAS, Lin and Liu 1998) has been extended with 2nd-order implicit scheme to better simulate field/prototype scale surf zone processes. However, it still requires lots of CPU-time to conduct field/prototype simulation. In the following year, we will collaborate with Dr. Losada's group at Universidad de Cantabria, Spain. They have been upgrading COBRAS using Fortran 90 with C++ library and the resulting code appears to compute several times faster than the our current version of COBRAS provided by Dr. Liu of Cornell University.

RESULTS

Measured near-bed flow velocity time series during CROSSTEX are used to drive the two-phase model. The model then reproduces fluid velocity, sediment concentration, velocity and sediment flux profiles from the immobile porous bed to the dilute regime of transport. For a given wave-current forcing, the breaking wave turbulence appears to enhance the magnitude of transport. Based on limited model simulations conducted at this point, such transport is often offshore directed due to strong undertow current: Concurrent measurements of wave velocities, turbulent velocity fluctuations and sand concentration are collected under random breaking wave trains near the bar crest during CROSSTEX (Scott et al. 2007). According to measured data, strong sand suspension events are often observed when breaking wave turbulence penetrates into the water column and approaches the wave boundary layer (WBL). Conventional boundary layer sediment transport models cannot incorporate the effects of free-surface generated turbulence on WBL. Here, we propose a new method where both the measured time-series of wave-current velocity and turbulence quantities (turbulent kinetic energy (TKE) and dissipation rate) are concurrently used to drive the two-phase model. Fig 1 presents the model results driven by measured 80 sec time series. The lower three panels show the model results for velocity, turbulence intensity and sand concentration profiles at three instants during the passage of a breaking wave train (top panel). When breaking wave turbulence does not approach the WBL (t1), model results obtained by using measured turbulence as top forcing (solid curve) and using conventional approach (dashed) are almost identical. Both methods predict similar sand concentration compared to measured data (crosses). However, when the breaking-wave turbulence is strong at (t2) and (t3), model results obtained by also using measure turbulence as forcing at top boundary shows strong TKE across the WBL. In addition, model predicted sand concentrations (solid) are similar to measured data (crosses) while conventional method fails to predict the suspension event (dashed). Despite the individual suspension events are strongly affected by the breaking wave turbulence, the time-averaged net transport rate for this case is only enhanced by 30%. This is possibly because the suspension events are usually of short duration compared to the overall length of the wave train.

On the other hand, using time series measured at other times, the net transport rate can be enhanced by factor 2 (not shown here). We also find that the result of net transport rate is rather sensitive to how we extract turbulence from the original velocity signal. Therefore, we decide to focus on more sophisticated data analysis technique using wavelet transform in order to identify the suspension events and their responses to steep wave and breaking wave turbulence. Such analysis will allows us to more objectively quantify the occurrence frequency of these suspension events and their relation to the forcing. Results obtain from such analysis can provide a more clear guideline for numerical modeling of sediment transport under breaking waves.

IMPACT/APPLICATIONS

The present research efforts focus on developing and validating detailed numerical models for sediment transport and wave hydrodynamics. We have focused on refining the numerical schemes in the two-phase model and RANS wave model so that they will be more robust and user-friendly in the future. It expected that by the end of this 4-year project, the two-phase model will be made available to the research community. Recent effort using wavelet analysis to study sediment transport under breaking wave is also new to the coastal sediment transport community.

RELATED PROJECTS

Hsu is currently supported by a NSF-OCE project: 3D Multiphase Sediment Transport Modeling Framework. This project focuses on extending the existing 1DV ensemble-averaged two-phase model for more detailed 3D eddy-resolving multiphase model. This model development effort will be extremely useful for the present research efforts to understand and parameterize sediment transport under breaking waves.

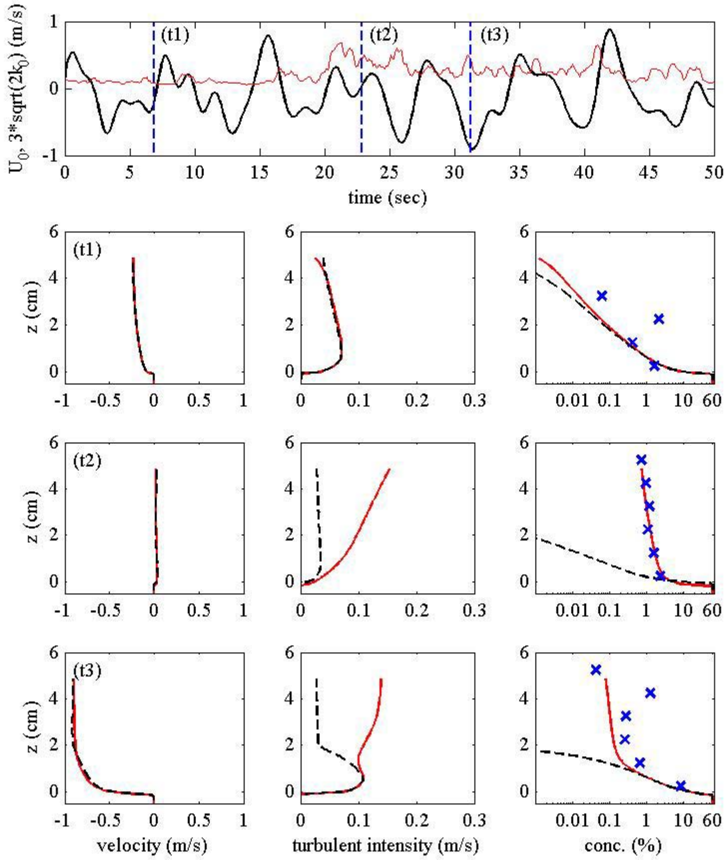

Fig 1: Two-phase model is driven by measured near-bed wave-current velocity and turbulence at 5cm above the bed during CROSSTEX (upper panel). In the lower panels (t1), (t2) and (t3) are model results for fluid velocity, turbulent intensity and sediment concentration. Black-dashed curves are results without considering the breaking wave turbulence while the red curves results when measured breaking wave turbulence is considered. Cross symbols are measured concentration. When the breaking wave turbulence is considered, the model is able to predict the suspension events observed during the experiment, suggesting the importance of incorporating breaking wave turbulence in modeling the bottom boundary layer sediment transport.

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HONORS/AWARDS/PRIZES

Tian-Jian Hsu, University of Florida, Faculty Early Career Development (CAREER) Award, National Science Foundation, OCE, 2007.